Satloc Real-Time Wide Area Differential GPS System

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Background

Satloc commenced development of its satellite based, Wide Area Differential GPS (WADGPS) network in 1995. Making use of key software licensed from the Jet Propulsion Laboratory (JPL), the network became operational in November 1996, and began providing differential correction signals to commercial users throughout the U.S. in May 1997. Satloc's development goals included: 1) to provide seamless nationwide coverage to Satloc applications customers coextensive with GPS coverage, 2) to reach accuracies in the sub-meter range, regardless of user proximity to a reference site, and 3) to maintain sufficient reliability and redundancy to achieve virtually 100% up-time.

The Network was extensively tested for six months before Satloc began offering differential service to commercial users. During the 11 months that commercial service has been available we have gathered additional data to confirm the operating performance. In addition, several Satloc customers and distributors engaged in offshore positioning in the Gulf of Mexico - where reliability is most critical - have tested the Network's performance over time. During the first 15 months of operation, the network achieved 99.997% availability. Root Mean Square (RMS) accuracies have been on the order of 0.6 meters in horizontal and 1.2 meters in vertical.

The State Space Approach

There are three approaches (Abousalem, 1996) to solving the Wide Area Differential GPS problem: 1) the measurement domain approach, 2) the position-domain approach, and 3) the state-space approach. The measurement and position domain algorithms effectively solve the problem by performing a weighted mean of the individual DGPS sites. The mean is taken either across the correctors themselves (measurement domain), or on the GPS position solutions resulting from using the individual DGPS sites (position domain). The state-space approach solves the problem more elegantly by computing the actual physical quantities comprising the pseudorange error. The advantages of this approach are: 1) it has superior spatial decorrelation properties so that performance is independent of reference station locations, 2) fewer reference sites are required, 3) minimal bandwidth is needed to transmit the data, and 4) performance degradation is insignificant for single reference site loss and degrades gracefully for multiple reference site loss.

For these reasons, the state space approach has been highly touted in professional literature (Kee et al. 1991, Mueller, 1994) and has become the basis for the Federal Aviation Administration's (FAA) Wide Area Augmentation System (WAAS) (Van Dierendonck and Enge, 1994). Satloc chose to take advantage of the findings in the literature, and selected the state-space approach for their WADGPS system.

The positioning accuracy achievable with GPS depends heavily on the accuracy of the measured pseudoranges. The pseudorange measurements are affected by GPS broadcast errors on both clock (primarily caused by SA) and ephemeris, atmospheric affects, and receiver noise including multipath. The error correction components provided by the state space solution and are shown in Table 1. Also shown is the approximate end-user error budget associated with each component for a receiver without any WADGPS corrections.

State Space Component	**Typical Contribution to User Position Error if Uncorrected**
Satellite (fast) Clock Corrector (includes SA)	20 to 100 meters
Ionospheric Correctors	3 to 10 meters
Satellite Orbit Corrections	0.5 to 2 meters
Troposphere	less than a meter with model

Table 1~~1~~ State Space Constituents and Associated User Error Budget

Of the state space correction components, the clock correctors which include SA, vary the most rapidly. The WADGPS signal includes a fast clock correction for every satellite tracked by the network and these are transmitted frequently (once per second). The ionospheric corrections are delivered to the user as a 2 degree map of vertical delays. The ionosphere map covers the CONUS and extends sufficiently beyond its boundaries to intersect pierce points of low-elevation satellites. The orbit corrections are delivered to the user as three deltas (Δx, Δy, and Δz) in Earth-centered, Earth-fixed (ECEF) coordinates.

Satellite clock correctors (sometimes referred to herein as fast clock correctors), and orbit correctors are computed using Real-Time Gipsy (RTG) software licensed from Jet Propulsion Laboratory (JPL). The Ionospheric corrections come from Real-Time Ionosphere (RTI) software, also licensed from JPL (Bertiger et al., 1998). Troposphere corrections, although computed at the Network Control Center (NCC) as part of the state space solution, are not broadcast to user equipment. Instead, troposphere effects are modeled within the user equipment since this is sufficiently accurate for most cases (i.e., the error resulting from the model is comparable to other sources of error).

In addition to the JPL algorithms, for redundancy reasons, Satloc has developed an alternate fast clock corrector algorithm with completely independent software implementation. Failure modes between the two fast clock algorithms are likely uncorrelated due this independence. Automatic rollover from one set of corrections to another increases reliability. Both the JPL algorithms and the Satloc algorithm are summarized in the section titled "Core Algorithms".

Network Infrastructure

The Network utilizes 14 reference stations situated throughout the continental U.S. to collect raw GPS observables. Figure 1 shows the geographic layout of the Network. The raw GPS data is delivered to two redundant Network Control Centers (NCCs) over independent frame-relay communication links.

The raw data arrives at the two NCCs (one in Reston Virginia and one in Scottsdale Arizona) in one second epochs. It is processed using a distributed software architecture hosted on multiple NT Pentium computers. The end result is packaged and sent to the Reston NCC where it is uplinked to American Mobile Satellite Corporation's (AMSC) Hughes-built, L-Band communication satellite. From the AMSC satellite the correction signal is broadcast across the United States and much of Canada and Mexico. Satloc L-Band receivers un-package the data, format it into standard RTCM messages and then deliver these messages to the GPS receiver.

Communications

Satellite L-Band Communications

The approximate L-Band coverage, provided by three separate beams, is shown in Figure 1. One major advantage of L-Band is that a single antenna is used for both the GPS correctors and the differential reception (Fig. 2). Other advantages include less receiver noise and ease of installation. Satloc's experience with localized beacons using 900 MHz and FM subcarrier, the Coast Guard's 300 kHz system, and Omnistar's C-Band satellite system inspired Satloc's choice of L-Band.

Terrestrial Communications

Terrestrial communications is typically TCP/IP over Frame Relay. Data is routed independently from each reference site to the two NCC facilities. Status and results data is also routed between the two NCC facilities. For critical paths dial-up phone lines provide extra redundancy.

Computer Communications

The NCC computers hosting the data processing, integrity monitoring, logging, and control software are linked together on an Ethernet network. Either TCP/IP or UDP (User Datagram Protocol) serve as the communications protocol. The UDP protocol, a one-to-many broadcast, is used most often since this makes the data available to all listening parties and thus gives any networked computer the potential to run any software module. UDP broadcasts are ideal for data which rapidly becomes obsolete with age and for which occasional missed messages can be tolerated. Most of the raw data falls into this category. The network is isolated from other networks so that traffic is minimized, therefore avoiding the potential for missed UPD packets.

Reference Site Equipment

Each reference station is located in a secured temperature controlled facility. Space is leased over long terms. Sites were selected to provide maximum visibility of the sky along with minimum multipath. Operational reliability of each reference station has been enhanced by minimizing the equipment required at the reference station (by centralizing computer processing and other functions at the network control centers).

The key component of the reference station is an Ashtech Z-12 GPS dual-frequency, geodetic quality GPS receiver. The Z-12 receiver connects to an Ashtech choke ring antenna. The internal Z-12 clock is used at all sites except the Olympia and Oceanside sites which use a Hewlett Packard 58503A external clock to drive the Z-12 receiver's clock. The HP clock contains a high quality quartz oscillator with a frequency accuracy of better than 1×10^{-12} per day.

A schematic for a reference site is shown in Figure 3. The important components are described as follows.

- Ashtech Z-12 Receiver – This is a codeless dual-frequency geodetic quality GPS receiver.
- Choke Ring Antenna – Hi quality antenna with choke-ring to minimize multipath.

- L-Band Receiver – Eight of the reference sites are equipped with Satloc's L-Band receiver. There are at least two of these located in each spot beam. The data collected by the L-Band receiver collected is sent back for integrity monitoring.
- Temperature Controller – The Ashtech receiver is enclosed in a temperature controlled container. Temperature is held constant at roughly 35°C to insure that receiver interfrequency biases remain nearly constant.
- Stable Clock – A Hewlett Packard 58503A external clock provides a clock input to Ashtech receivers in two of the reference sites. At least one stable clock is required if true GPS time is to be solved for across the network. This is actually not necessary from purely a positioning standpoint since a uniform clock bias is removed at the receiver. However, it is a nice feature since it enables the user equipment to precisely determine time.
- Terminal Server – DECSERVER 90M terminal servers are used to provide a communication interface between RS-232 and Ethernet TCP/IP protocols. All data is shipped over the Frame-Relay as TCP/IP packets.
- UPS – a UPS provides un-interrupted power. The UPS notifies the NCC control center if AC supply power has been lost.
- Remote Power Switch – This allows the remote equipment to be re-booted from the Scottsdale NCC.

NCC Equipment

The Network Control Center (NCC) equipment is similar for both Reston and Scottsdale. This equipment includes communications support equipment, monitoring equipment, computer processing equipment and battery back up power equipment. Figure 4 is a photograph of the Scottsdale NCC Facility. Below is a list of the major components

- Pentium based PC's – All software is hosted on Pentium PCs running Windows NT with 32 megabytes of memory and at least 2 Gigabytes of hard-disk space. In Scottsdale, desktop PC's are used, while rack-mounted industrial PC's are used in Reston.

- Routers and CSU/DSU – These provide connectivity from the local Ethernet to Frame Relay network.
- L-Band Modulators – A bank of L-Band modulators exists only at the Reston facility. There is a pair of modulators for each spot beam. Only one modulator of the pair actually modulates the signal onto the satellite. The other modulator is in "hot" standby mode, and is switched in if commanded by the NCC integrity monitoring software.
- Mux Control – An RF relay for each spot beam switches between the two modulators.
- UPS – A UPS provides un-interrupted power. The UPS notifies the NCC control center if AC supply power has been lost.
- Remote Power Switch – This allows the Reston NCC equipment to be re-booted from the Scottsdale NCC.

Software Functionality

There are many different software modules deployed within the NCC to serve the needs of data processing, differential corrector generation, message scheduling, control, monitoring and data logging. We will not discuss each module in detail, but will instead concentrate on the core tasks that are solved through software implementation. A simplified schematic of the software flow is provided in Figure 5.

State Space Correction Software

Generation of the state space correctors starts with the data collection and distribution processes. Raw GPS and other sensor data is collected over TCP/IP connections, re-formatted and sent to all computers within the local NCC as UDP datagram broadcasts. The GPS data from the remote sites is collected at one second epochs. After 1.4 seconds from the epoch all subsequent GPS data for that epoch is discarded to avoid added latency. During normal operation data is occasionally discarded but this occurs less than 0.2% of the time and does not affect performance.

Many software modules use the UDP broadcast of the raw data, the primary ones being the fast-clock, orbit, and ionosphere software. These run simultaneously on separate NT machines. The fast clock correctors are computed at one-second epochs and then broadcast over the local Ethernet for eventual use by other processes. The orbits and ionosphere modules collect data continuously, and then process the collected data at 5 minute epochs. The resulting orbit files, ionosphere map, and some intermediary data are then distributed to those software modules within the NCC which use the results. There is some interdependency between the algorithms. For example, orbits, troposphere and earth-orientation data generated by the orbits process is used by the JPL (RTG) fast clock process and the orbit data is used by the Satloc fast clock process.

The next step in the software flow is that of formatting the message into the structure which will be broadcast on the L-Band satellite. At this step the results of the fast-clock, orbits and ionosphere processes are combined together into the final message -- a 750 bit-per-second message with a header and 24-bit cyclic redundancy check (CRC) for each 250 bits of data. Some additional manipulation of the data also occurs at this step. For example, it is at this step that the difference between the RTG precise orbits and the GPS broadcast ephemeris is formed. In addition, this is the point where general communication information, such as subscription updates and text messages is injected into the message stream.

The last step prior to modulation on the satellite L-Band signal is scrambling, Viterbi encoding and discrete-time filtering of the data. The original 750 bit-per-second message is converted to 1500 bits-per-second due to the Viterbi encoding. It is then sampled at 12 kHz for filtering and finally converted to analog as it is fed to the L-Band modulator hardware.

Integrity Software

While the software involved directly in the generation of the corrections is running, other software continuously monitors the integrity of the system. At the Scottsdale NCC, GPS solutions are computed for each of the 14 reference sites using both the Reston and Scottsdale WADGPS corrections. The Scottsdale GPS observables are used for both sets of solutions. Should either solution set appear significantly worse than the other (i.e., 2 meters on the average across the best 13 reference sites: the worst reference site is discarded from the average) the mux control in Reston is commanded to engage the modulator corresponding to the better performing NCC.

The integrity software also monitors total system performance by closing the loop from the point-of-generation to point-of-use. At eight of the remote reference sites, Satloc's L-Band receiver has been installed. At least two receivers are situated in each spot-beam. The L-Band signal which has been received over-the-air is shipped back to the Scottsdale NCC where it is compared to the original broadcast values from both Reston and Scottsdale. If a match is found then the data is good. If not and the failure seems global or local to a certain spot beam, the modulators within the bank are switched as appropriate to alleviate the problem. If the problem does not correct itself in a reasonable amount of time, the modulators are switched again. This continues until the problem is resolved. We point out that by closing the loop, we also monitor total system latency.

Much of the integrity monitoring is distributed throughout the many separate processes running within the NCC. The data, as it is collected, is tested for soundness. This includes checksums, time-stamp validity, ephemeris validity, and even the Ashtech receiver's internal GPS solution validity. If the Ashtech's solution is bad, there is a potential that the raw observables are corrupted and thus should not be used. Invalid data is either removed completely or flagged so that it is not used.

The clock, ionosphere and orbits processes all edit their incoming data. Outliers and other suspicious data are eliminated up-front by performing tests on carrier phase breaks and by monitoring the innovations of the Kalman filter. The Satloc clock filter also performs outlier detection through data clustering techniques.

It should be mentioned that data which has been flagged as invalid in the GPS broadcast is not used. For example, if a GPS satellite is being repositioned, it is eliminated from use by the algorithms. Furthermore, the RTG orbit software automatically detects GPS satellite maneuvers- even if they are not reported in the GPS broadcast.

Display and Data Logging Software

Display

Visual aids, in the form of graphical user interfaces (GUI) are available to assist the operator in diagnosing problems. Real-time charts and maps are displayed which show incoming as well as outgoing data. The display of incoming data includes the GPS observables, in both summary and detailed presentations, temperature data from the remote sites, and L-Band receiver data. The outgoing GUI display includes every component of the state space correction message, as well as a scatter chart of positioning errors (Fig. 6). Color coding is used on many of the GUI displays, where "red" alerts the operator of problems, and "green" means all is the system is operating correctly and within tolerances.

Errors in integrity or other potential problems are logged by the system. More severe errors cause a flashing message and beep to alert the operator of the problem. Dial-in capabilities to the Network are provided so that the Network can be monitored from off-site locations.

Data Logging

Raw data is logged on a continual basis and stored on large capacity hard-drives. This data, which accumulates at a rate of about a gigabyte per day, is off-loaded to a writable CD if it is deemed of interest or overwritten if not. We have implemented a real-time play-back utility for this data to aid in algorithm development and problem diagnostics.

In addition to the raw data all status messages are logged. Internal software reports which are not critical are logged to a circular file. All other messages are logged and kept indefinitely.

Also logged are the GPS position solutions and signal status from the remote L-Band monitor stations. These are logged continuously and automatically archived daily. Using these archives, it is easy to go back and search for network problems.

Fault Tolerance

The WADGPS system is designed to prevent any single failure from taking down the entire network. This occurs both at the hardware and software level.

Hardware:

The Network Control Centers are fully redundant with both centers performing identical tasks. A redundant set of modulators has been installed for each of the spot beams. Communication between the reference sites and the NCC facilities is separate and independent. Loss of a reference site causes minimal impact due to the nature of the state-space solution (with 14 reference sites, probably a third could be considered as backups). Communication between NCC facilities is backed by dial-up phone.

Due to the architecture of the software, redundancy of the computers is built in. Each PC is capable of running any software module and has plenty of spare CPU. If one machine fails, then another machine can stand in for it until it is repaired. The time required to restart software is in the matter of seconds. As described next, some of the core software is backed up by "hot" standbys running on separate machines which automatically take over if necessary.

Software:

The fast correctors are generated by totally independent software algorithms with one algorithm running in Reston and the other in Scottsdale. The ionosphere process and orbit process, though the same in both Reston and Scottsdale, are provided with software backups. Should the ionospheric process fail, the previous day's ionosphere is automatically played back as though it were real-time. This is often sufficient since the ionosphere is likely to be similar from day to day. The orbits process is backed by a smoothed version of the GPS broadcast ephemeris. To date, neither the orbits process nor the ionospheric process has ever failed. Only the early development versions of the fast-clock processes have failed (produced bad results), but never simultaneously.

Since the fast clock correctors are the most crucial to real-time performance, an additional step is taken to guard against very short outages which might be caused by frame-relay "glitches" and momentary loss of GPS observables. The software which packages the 750 bit-per-second message runs a Kalman filter on each clock correction it receives. This Kalman filter models the clock correctors down to the acceleration state. Should an brief lapse occur in the normal flow of clock correctors the Kalman filter will fill in with its best estimate, extrapolated over time using a constant acceleration profile. This method works well for 10 and even 20 seconds of loss of fast clock correctors. This approach has in fact allowed us to upgrade the fast clock software by shutting down and restarting with the upgraded version without a noticeable loss in performance.

The software is also robust to faults at the communications level. A client-server approach is taken in the in the software which provides connectivity. In the event of a TCP/IP failure the client-side software repeatedly attempts to re-establishes communications with the server until the connection is finally made. In some instances the failure may induce the software to shutdown, and restart itself as a last resort.

The Reston NCC facility has a direct connection to the modulators which feed the uplink to the L-Band satellite. If communication between Reston and Scottsdale is lost the software at Reston will assure that the modulator bank will be switched to broadcast the Reston signal. The Reston signal, since generated at the point-of-use, can never be interrupted as a result of communication network failure.

Because of the built-in capability of the NCC software to handle faults, the NCC rarely needs operator intervention.

Core Algorithms

JPL Algorithm Summary

Figure 5 gives the overview of the WADGPS state space solution, with each major process shown in rectangular blocks along with the overall data flow. Details of the orbit, ionosphere, and fast clock processes appear in Bertiger (Bertiger, et al. 1998). Here we just give a brief overview. Much of the software and algorithms are based on the well tested, highly accurate GIPSY/OASIS II (GOA II) software (Wu, et al. 1990, Webb et al., 1993). GOA II has a long history in precise orbit determination for both GPS and other orbit spacecraft (Bertiger, et al. 1994; Gold et al., 1994; Haines et al., 1995; Muellerschoen et al., 1995) and in precise GPS geodetic applications (Heflin et al., *1994;* Argus et al., 1995). GOA II consists of a set of mostly FORTRAN programs and UNIX scripts which would be difficult to port to non-UNIX environments and real-time applications. To overcome these limitations a new software set, Real-Time Gipsy (RTG), was written to support WADGPS and other possible real-time applications in embedded systems. (for example, NASA's X33, on-board satellite orbit determination and real-time position for NASA's Synthetic Aperture Radar (SAR) aircraft).

GPS Orbit Determination and Troposphere Calibration

The RTG orbit process is an extended Kalman filter which processes dual-frequency measurements of pseudorange and phase every 5 minutes. 1-Hz pseudorange is smoothed (Hatch smoothing: Hatch, 1982) with the 1-Hz phase to produce uncorrelated 5 minute pseudorange points; biases are re-determined every 5 minutes or at phase discontinuities. The phase is simply decimated at the 5 minute mark. The phase bias is not leveled with pseudorange but rather estimated in the orbit process. In this way the phase measurements also remain uncorrelated in time. Filter states include GPS position and velocity, GPS clocks, ground network clocks, zenith troposphere delay at each ground station, earth orientation parameters, and carrier phase bias parameters. The GPS position and velocity are updated in the numerical integrator after processing each batch of 5 minute measurements (extended filter). The orbit integration uses a 12x12 gravity field and a precise solar pressure model. After updating the GPS position and velocity, the orbits are propagated 20 minutes into the future for use in the fast correction process which solves for the 1-Hz GPS clock updates. The orbits have been compared to post-process truth orbits (good to 10-20 cm) and shown to have an RMS accuracy of about 1-meter in the region relevant to the user. In addition to the orbit parameters, the process passes off the value of the troposphere at each ground station to the fast process. The troposphere has an RMS accuracy of 1-2 cm.

Ionosphere Corrections

The process for generation of precise real-time ionospheric delay corrections utilizes a modified version of the Global Ionosphere Map (GIM) software developed at JPL (Mannucci, et al. 1993). The GIM software set consisted of FORTRAN programs and UNIX scripts, so for portability and real-time applications a new software based on GIM algorithms was developed--Real-Time Ionosphere (RTI). RTI models the ionosphere as a shell above the earth in a sun-fix reference frame. The sun-fixed frame is chosen since the ionosphere has less time variation in that reference frame. The shell is discretized into triangular elements and the total electron content (TEC) for each of the nodes of the triangles becomes a state in the Kalman filter. The nodal values are treated as random walk parameters. Initialization constraints are supplied by the Bent model (Bent et al. 1976). The data for the filter consists of phase differenced at the two GPS frequencies (L1 – L2) with the level adjusted by smoothing against differenced range (P1 – P2). Biases at both the receivers and the GPS transmitters, between the data at the two GPS frequencies must be accounted for by the RTI process. These biases are held constant in the real-time process and are monitored off-line in a simultaneous solution for TEC and the biases relative to a well calibrated or stable receiver. A detailed list of the GPS inter-frequency biases and the effects on user positioning is contained in Bertiger et al. 1998. Detailed tests with data in 1996 showed the ionosphere to be accurate to 20-30 cm (Bertiger et al. 1998).

Fast Clock Corrections

For every satellite viewed by the network, a correction to the GPS range is computed every second. This correction is solved for as a correction to the GPS clock, which is estimated simultaneously with the receiver clocks . This allows for isolation and identification of error sources as GPS or receiver problems. Note that even over North America some orbit error is common to all the receivers viewing GPS and is absorbed by the GPS clock solution.

Figure 7 is a block diagram of the process. Almost all of the computation can be carried out during the network communication process and thus the fast correction computation adds only about 2 msec to the latency of the corrections. Raw data are read in and adjusted by the Ashtech receiver navigation solution (except for the receivers with stable reference clocks) to keep the station clock solutions within SA bounds and allow easy error detection. The editor continuously smoothes the range measurements with the phase measurements until a cycle slip is detected at which point the smoothing is reset. Unlike the orbit process, only the smoothed range is processed. The most computational intensive part, the measurement model is computed 1-sec in advance of real-time, so as not to delay the output of the GPS corrections. Clock parameters are treated as random-walks by the filter allowing outlier detection by the filter. There are options in the process to use either dual-frequency data to eliminate the ionosphere effects or to read in the ionosphere map sent to the user.

Satloc Fast Clock Corrections

The Approach

The Satloc clock filter takes a slightly different approach than does the JPL-developed, RTG clock filter. For example, the Satloc clock filter determines receiver clock biases algebraically, and then uses a Kalman filter to simultaneously estimate troposphere delays and satellite clock error. The JPL clock filter does not estimate troposphere delays, but rather obtains these from the RTG orbits process. A Kalman filter is then used to simultaneously estimate satellite clock error and receiver clock biases.

The Satloc and JPL clock filters are also similar in certain respects. Both make use of the precise orbits from the RTG orbits process. In addition, both filters eliminate the ionosphere effects by using the Ashtech's dual frequency (L1 and L2) observables. Clock correctors based on the dual frequency approach are later adjusted to make them valid for single-frequency users. As an option, both filters are capable of using only L1 data, where the ionosphere delay values are taken from the ionosphere map provided by the RTI process. We are currently using the L1-only option as the default since it has given slightly better performance on an L1-only receiver.

Clock Filter Implementation

The clock filter starts out by carrier phase smoothing the measured pseudoranges for all observations taken across the network. The carrier phase filter consists of a 3-state Kalman filter modeling acceleration as a first-order Gauss Markov process. Modeling down to the acceleration state is ideal for stationary receivers since it gives fairly accurate predictions of pseudorange even while coasting. Inputs to the filter are code and delta-carrier-phase (change in carrier phase). Delta-carrier phase is used, rather than accumulated-carrier-phase since this enhances the ability to detect cycle slips. Cycle slips can be detected simply by monitoring the residuals of the Kalman filter.

The clock filter then computes, for each satellite observation at each receiver, a value that we shall refer to as *SAmeas*. *SAmeas* is the difference between our estimate of the satellite's true range and the carrier-smoothed pseudorange, accounting for ionosphere delays, broadcast satellite clock bias, receiver clock bias and modeled troposphere. That is, if noise effects and modeling errors are neglected the following equation holds

SAmeas =
True_Range - PseudoRange - SV_clock + Receiver_Clock + Modeled_Tropo +
(Iono_Delay)

The *Iono_Delay* term is placed in parenthesis since it is only included if the clock filter is configured for the single frequency solution. In determining *True_Range*, the precise orbits from the RTG process are used along with the known precise locations of the reference sites. The model of troposphere employs the Niell mapping function (Niell, 1996).

Effects that are not evident in the equation are unmodeled troposphere and ionosphere, perhaps a small receiver clock bias not accounted for by the *Receiver_Clock* term (often corrupted by SA), and receiver noise such as multipath. These will be dealt with shortly.

As can be seen, *SAmeas* roughly equates to satellite clock error. It is dominated by Selective Availability (SA). Figure 8 is an example showing the typical constituents of *SAmeas* for a receiver tracking 4 satellites. Notice that the receiver clock bias is the same for all PRNs. This can then easily be differenced away if we choose a suitable reference PRN. The difference equation becomes

SAdiff(i) = SAmeas(i) - SAmeas(M) + UnmodeledTropo*[1.0/SinElev(i) - 1.0/(SinElev(M)] + noise

where 'i' denotes an arbitrary PRN and 'M' is the reference PRN. This time the unmodeled troposphere is shown, as it shall be important to the ensuing discussion. The unmodeled troposphere is mapped into the line-of-sight by dividing by the sine of the elevation angle—a simple but sufficient mapping. If present, unmodeled ionosphere is lumped into the *noise* term.

The *SAdiff* equation can be interpreted as an observation equation including both relative satellite clock error and unmodeled troposphere. By "relative", we mean that the clock error is relative to the reference satellite's clock.

For each satellite tracked by the network, the *SAdiff* observations are fed to a multi-state Kalman filter. The Kalman state vector consists of the relative clock errors for each satellite PRN and troposphere at each receiver. The Kalman filter assumes a first-order Gauss Markov process on both types of state. The process noise is set fairly low for the troposphere states and is set to a moderate value for the clock error states. Decay time-constants of several hours are used for the troposphere Gauss Markov model, while 30 second decay time-constants are applied to the satellite clock model. For numeric stability, the Kalman filter covariance propagation employs factored UD formulation (Bierman, 1977; Thornton, 1976).

An important topic is that of selecting a suitable reference PRN. The methodology applied here is to choose a satellite that is visible to all of the network reference stations (one always is) and hold onto it as long as possible. When its is time to change reference PRNs, the Kalman filter states are adjusted accordingly. That is, the difference between the old and the newly selected state of the reference PRN is added to all clock states.

The final issue is how to get the clock error estimates relative to true GPS time rather than time of the satellite corresponding to the reference PRN. Although not necessary for purely positioning applications, it is desirable for two reasons: 1) the GPS receiver needs correctors referenced to true time if it is to produce accurate estimates of GPS time and 2) it avoids discontinuities in the correctors as a result of reference PRN changes.

This is where the sites with the stable reference clocks come to play. First, the *SAmeas* values from each site are shifted by a constant (a different constant for each site) so that they "best" agree with those of a stable clock site. By "best" we mean that the elevation-weighted difference across all common PRNs is minimized. If a stable clock site is not available, the *SAmeas* values are shifted to best agree with those of an arbitrary site, which itself, has been adjusted to make its *SAmeas* values close to zero mean.

Next, a mean corrector is formed for each PRN by averaging the adjusted *SAmeas* values across all sites, again weighting by elevation angle. These mean values are, in fact, very close to the clock correctors we desire, only that they are corrupted by unmodeled troposphere. We refer to the mean values as "approximate correctors"

By simply adding the "approximate corrector" for the reference PRN to each corrector produced by the Kalman filter, we put true GPS time back in. The averaging performed while generating the "approximate correctors" mitigates noise effects. Although time may be skewed slightly by the unmodeled troposphere within the "approximate corrector" of the reference PRN, the relative nature of the Kalman states is preserved. That is, unmodeled troposphere effects are eliminated.

As expected, there are a whole host of other considerations, such as dealing with bad data, which must be dealt with in a practical implementation of the aforementioned clock filter. The Satloc filter employs data editing and validating techniques which have given sound results. One technique has been detecting outliers by clustering data. A number of other checks are made, but they will not be discussed here.

Reference Receiver Positioning

For a WADGPS network to perform correctly, all reference station receivers must be accurately positioned. More than this, they must be positioned in a coordinate system which is consistent, well defined, and global (at least over the area of coverage). International Terrestrial Reference Frame (ITRF) is such a coordinate system. Leading scientific agencies have made substantial investments in the ITRF global reference frame and have established it as a centimeter level accuracy frame.

The reference stations were positioned to centimeter level using Gipsy Oasis II (GOA II) software with data from the IGS global network of receivers. The locations of the receivers within this global network are know to the centimeter level and are expressed in the ITRF94 reference frame. The positioning methods are described in Zumberg (Zumberg, et. al. 1997, p. 5005-5017).

Because our network data is available on a continuous, real-time basis, we were able to produce centimeter level coordinates of a receiver's location within 24 hours of the receiver being brought on-line. Changes in the receiver locations are monitored periodically.

Implications to the User Equipment

Although not obvious, the reference coordinate system of the WADGPS network also becomes the reference system for which the GPS receiver outputs its position. Because Satloc uses ITRF94 coordinates, all GPS positions using the Satloc system are relative to the more accurate ITRF94—not WGS 84. For the user, the implications of this are minimal: ITRF94 and WGS 84 now agree within the errors of WGS 84 (Malys, et al. 1997; NIMA WGS 84 Update Committee, 1997).

The reason that the GPS user receiver outputs its position relative to ITRF94 can be attributed to the nature of the satellite orbit corrections (provided in the state space broadcast). The corrections, when added to the broadcast orbits, are the positions of the GPS in ITRF 94. Thus the user receiver is in that coordinate system.

L-Band Signal

The WADGPS signal arrives at the end-user's L-Band receiver with a total latency of less than 4 seconds. The signal contains all the state-space components and supporting messages and is processed by the L-Band receiver to form a standard Type 1 RTCM message which is delivered to the GPS receiver.

Signal Structure

The Satloc WADGPS signal has some commonality to the WAAS signal specification as should be expected since both the Satloc and WAAS systems use the state space approach. The Satloc signal is a 750 bit-per-second broadcast, consisting of 250 bit packets each with preamble and 24 bit CRC. Each packet has an associated category. These are shown in Table 2.

Message Category	Message Description
PRN Mask	This message contains a bitmap of the satellite PRNs currently available in the fast clock and orbit corrections. The clock and orbit correctors are kept in sync with this bitmap, even though their transmission rate is different
ZS Count	Time stamp required to align the message with GPS time.
Iono Vertical Delay Map	The ionosphere vertical delay map is transmitted in a 2 degree grid covering the CONUS and far enough beyond the CONUS to account for low elevation satellites at the borders. Much of the ionosphere delay values are used to fill spare space within the other messages.
Orbit Correction	The 3 component, Δx, Δy, and Δz between the GPS ephemerides and the RTG precise orbits in ECEF coordinates. Multiple, consecutive messages are required to transmit corrections for all satellites in view.
Almanac	These are very condensed almanacs that give the L-Band receiver knowledge of satellite positions without it relying on the GPS receiver. Satellite positions are needed for projecting orbit and ionospheric corrections into the line-of-site of the satellites.
Fast Clock	This message contains the fast clock correctors.
Subscriber, Receiver, Client	Messages for sending text to a remote user, updating receiver parameters over-the-air, and changing subscription level and expiration.

Table 2~~2~~. State Space, WADGPS Message Categories for Satloc L-Band Signal

The message structure supports a maximum of 18 satellites in view by the network at one time. A typical value is about 10 satellites, while 13 is rarely (if ever) exceeded.

Notice that we do not transmit an accuracy term. We have taken the philosophy of letting the Network Control Center determine what should and shouldn't be used since it is better able to make this determination. Bad or degraded data simply is not transmitted. The network integrity algorithms assure this approach, which in addition to simplifying receiver software, has proven quite effective. In extensive testing, adverse effects on receivers due to bad data have not occurred, and sub-meter positional accuracies attest to this approach.

Message Scheduling

The various categories of messages are scheduled for transmission according to dynamically determined priority. The rapidly changing fast clock correctors are always given high priority and are transmitted each second. The addition or subtraction of a satellite causes a priority boost in the effected messages: namely the PRN mask, fast clock and orbit correctors. Priority also changes as a function of the age of the last transmission of the particular message with higher priority given those messages which have not been scheduled recently. On the average, the orbit corrections tend to be broadcast about once every 10 seconds. This is more than adequate since these corrections remain nearly constant for a period of minutes. The ionosphere vertical delay map is intermingled with other messages, and it takes roughly one minute to completely refresh. The ionosphere map is transmitted by interleaving both the rows and columns so that that it only takes several seconds to get a coarse representation of the ionosphere over the CONUS. Figure 9 depicts the approximate timing relationships of the crucial state space messages.

Since messages are scheduled at different transmission rates, it is important to keep the messages synchronized so that terms such as clock correctors and PRN masks are not mismatched. The NCC software handles much this complexity sparing the L-Band receiver of an unacceptable software burden. The NCC software also adds synchronization keys to the messages to aid the L-Band receiver in deciphering the messages. The original design goal, which has been met, was to allow the receiver to function correctly while randomly missing 50% of the messages.

Subscriber, Client and Receiver messages get scheduled in the excess capacity of the network (approximate 250 bits-per-second). Should more capacity be required, a gradual slowing of the less time-critical WADGPS messages will occur, but only to the extent that the slowing will not degrade performance. So far, the excess capacity has been more than sufficient. When the excess capacity is not being utilized it is stuffed with almanac messages.

L1 Receiver Compatibility

The state-space correctors are valid for a single frequency (L1-only) user receiver tracking C/A code. This is true even though the internal algorithms utilize ionospheric-free combinations of PY code pseudoranges provided by the Ashtech Z12 receiver (PY code pseudoranges are much less noisy than C/A code pseudoranges). Adjustments are made to the final clock-correctors to account for the inter-frequency biases between L1 and L2 as well as biases between PY and C/A code (CA-PY biases). The end product is always correct for the single frequency user.

In order to have the end-result relative to a L1 receiver tracking CA code, it is necessary to have a good estimate of both inter-frequency biases and CA-PY biases for all satellites. Inter-frequency biases are updated on roughly a monthly bases using a special configuration of their RTI software. The CA-PY biases are estimated continuously by the fast-clock filters.

A related problem, which must be contended with, is that of the GPS broadcast value of Group Delay, often denoted as $\tau_{gd,}$ the broadcast value of inter-frequency bias. Single frequency receivers will use the GPS Group Delay, even when accepting differential correctors. Unfortunately, however, the broadcast Group Delay is seldom accurate (Bertiger et al., 1998). Satloc compensates for this by adding the negative of τ_{gd} to the clock-correctors. The correct Group Delay is already inherent in the clock-correctors since they are adjusted to be applicable to L1 using the JPL generated inter-frequency bias.

If the Satloc WADGPS corrections are to be used in dual-frequency user equipment, then it is necessary to remove the inter-frequency biases inherent in the clock-correctors. Since these biases are fairly stable, it is possible to supply them to the positioning algorithm as a table of constant values. This was done when performing real-time test using dual-frequency TurboRogue receivers.

Receiver Side Algorithms

Both the WADGPS correction signal and the GPS signal are received through a single antenna. The GPS data is processed by an internal GPS receiver and the WADGPS correction signal is processed by the L-band Receiver. The L-Band Receiver and the GPS receiver communicate over a serial port using standard NMEA and RTCM message formats.

The receiver software is responsible for converting the broadcast state space data into differential corrections tailored for use at the receiver's current location. Differential corrections are computed with knowledge of the user's position (provided in the NMEA message from the GPS receiver) as is required for projecting the state-space, global components into the localized pseudorange correctors. The end result is a unique differential correction that has been optimized for the user's current location; having an accuracy that is independent of this location.

Differential Correction Format and Formulation

For a high degree of compatibility, RTCM Type 1 SC-104 was chosen as the format for sending the differential corrections to the GPS receiver. It is supported by virtually all "high-end" and many "low-end" GPS receivers. RTCM Type 1 contains the following components: Zcount, PRCs, RRCs, and IODEs.

Zcount

Zcount is the time at which the PRCs, RRCs and IODEs are valid. The PRC typically has some latency when it arrives, and the Zcount is used in determining the time difference needed for extrapolation.

PRCs

PRCs (pseudorange corrections) are corrections to the receiver's measured pseudorange. For the state space approach these become the sum of clock, orbit, ionosphere and troposphere correction terms.

The message containing the complete set of fast correctors is received over the L-Band link at a one second rate. Each fast correction is processed by a 3-state Kalman filter which in addition to smoothing the correction, forms an estimate of the correction's first and second derivative. In the event of a missed message or temporary loss of lock, the Kalman filter is used to provide 2^{nd} order (constant second-derivative) prediction of the PRC. In addition, the Kalman filter's estimate of fast corrector rate (first derivative), becomes the RRC in the RTCM message since rates are not broadcast as part of the L-Band state space message.

The 3 dimensional orbit correction vector is projected into the satellite's line-of site prior to being added to the PRC. This is accomplished by forming the dot product with the unit vector pointing to the satellite. The satellite's position is known since both time and almanac messages are part of the Satloc broadcast signal.

As mentioned above, ionosphere corrections are received as a map of vertical delays covering the CONUS in a grid of 2 degree resolution. The receiver software first determines the vertical delay at the intersection of the satellite's line-of-sight vector with an assumed ionospheric shell of fixed altitude. This vertical delay is then converted to a slant delay using an obliquity based on elevation angle. The vertical delay at the shell intersection (pierce-point) is established by interpolating the 4 nearest vertical delays from the 2 degree map.

Troposphere corrections to pseudorange are computed from a model where wet and dry components are mapped to the line-of-sight using the Niell formulation (*Niell*, 1996). The inputs to the model are latitude, satellite elevation angle, user height, time and date.

RRCs

RRCs (range rate corrections) contain the rate at which the PRC is changing. They are needed to extrapolate the PRC to the time of the GPS observation. The rapidly changing nature of SA makes the fast corrector by far the largest contributor to the RRC. Consequently, Satloc applies only the fast corrector's rate-of-change when generating the RRC (the orbital and ionospheric rate contributions are negligible). As indicated, this rate is estimated with the aid of a Kalman filter.

IODEs

IODEs (Issue of Data Ephemeris) is an identifier of the ephemeris for which the pseudorange correction has been referenced. When forming the navigation solution, the GPS receiver must assure that for each satellite the IODEs in the pseudorange corrector and ephemeris match. Satloc broadcasts orbit corrections, along with their identifying IODE beyond the point at which the GPS User Segment changes the broadcast value of the satellite's ephemeris. This gives the GPS receiver multiple opportunities to capture the new ephemeris before being supplied with correctors which reference it. We do not transmit RTCM Type 2 messages containing delta differential corrections during ephemeris crossovers because most GPS receivers will buffer new ephemerides until their IODEs match those of the differential correctors.

Other Receiver Functions

The receiver's RS-232 port may be configured to output both RTCM differential corrections for use in an external GPS receiver and differentially corrected NMEA from the GPS receiver embedded within the unit. Also available via the RS-232 port are text messages which are sent over the L-Band link to target either an individual user, or a group of users belonging to a single fleet (having the same fleet ID). Over-the-air signal subscription updates and receiver re-configuration messages are also handled by the software.

Performance Results

Figure 10 shows position results using a stationary Ashtech Z-12 GPS receiver, differentially corrected with the RTCM output of a Satloc L-Band receiver. By using a "high-end" Ashtech receiver, a clearer depiction of network performance is obtained with less skewing of the results due to receiver noise.

The Ashtech Z-12 is attached to a choke-ring antenna. It uses only the L1 observables when solving for position. The receiver is situated in Scottsdale, a location which is hundreds of miles from the nearest network reference site. The location originally had served as a reference site in the early days of the network development and so was accurately positioned along with the rest of the network reference sites. The plot shows that over 24 hours, the horizontal RMS is 0.6 meters. This is a value typical of what has been observed over many days of monitoring network performance. Vertical positions are less accurate—typically larger than horizontal by almost a factor of 2.

Higher accuracies can be obtained by processing the Ashtech's raw observables with our own software algorithms (Bertiger et al., 1998), with 30 to 40 cm RMS errors in horizontal, and about 60 cm in vertical. We have also demonstrated high performance during dynamic tests in which the receiver antenna was mounted to the roof of an automobile driving under freeway conditions.

Summary and Conclusions

Satloc has developed the first commercial state space WADGPS system serving the continental United States. The state space approach was chosen for its technical merits, including low data rate, reduced numbers of reference sites, and location-independent accuracy. For the highest degree of compatibility, we have developed an L-band receiver which internally converts the state space message into localized RTCM differential correctors.

We have undergone considerable effort to assure accuracy and reliability of their WADGPS network. This effort has paid off: we have shown a 99.997 availability over 15 months and accuracies have been well under a meter. We are continuing to refine and improve the network's performance. Software and algorithm enhancements are easily incorporated due to the centralized nature of the network's processing.

In addition to commercial uses of the network, we have demonstrated high accuracy navigation onboard a NASA SAR imaging aircraft. Further demonstrations will be aboard the X33, NASA's successor to the space shuttle.

Acknowledgments

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Figures

Tables

State Space Component	Typical Contribution to User Position Error if Uncorrected
Satellite (fast) Clock Corrector (includes SA)	20 to 100 meters
Ionospheric Correctors	3 to 10 meters
Satellite Orbit Corrections	0.5 to 2 meters
Troposphere	less than a meter with model

Table 1. State Space Constituents and Associated User Error Budget

Message Category	Message Description
PRN Mask	This message contains a bitmap of the satellite PRNs currently available in the fast clock and orbit corrections. The clock and orbit correctors are kept in sync with this bitmap, even though their transmission rate is different
ZS Count	Time stamp required to align the message with GPS time.
Iono Vertical Delay Map	The ionosphere vertical delay map is transmitted in a 2 degree grid covering the CONUS and far enough beyond the CONUS to account for low elevation satellites at the borders. Much of the ionosphere delay values are used to fill spare space within the other messages.
Orbit Correction	The 3 component, Δx, Δy, and Δz between the GPS ephemerides and the RTG precise orbits in ECEF coordinates. Multiple, consecutive messages are required to transmit corrections for all satellites in view.
Almanac	These are very condensed almanacs that give the L-Band receiver knowledge of satellite positions without it relying on the GPS receiver. Satellite positions are needed for projecting orbit and ionospheric corrections into the line-of-site of the satellites.
Fast Clock	This message contains the fast clock correctors.
Subscriber, Receiver, Client	Messages for sending text to a remote user, updating receiver parameters over-the-air, and changing subscription level and expiration.

Table 2. State Space, WADGPS Message Categories for Satloc L-Band Signal

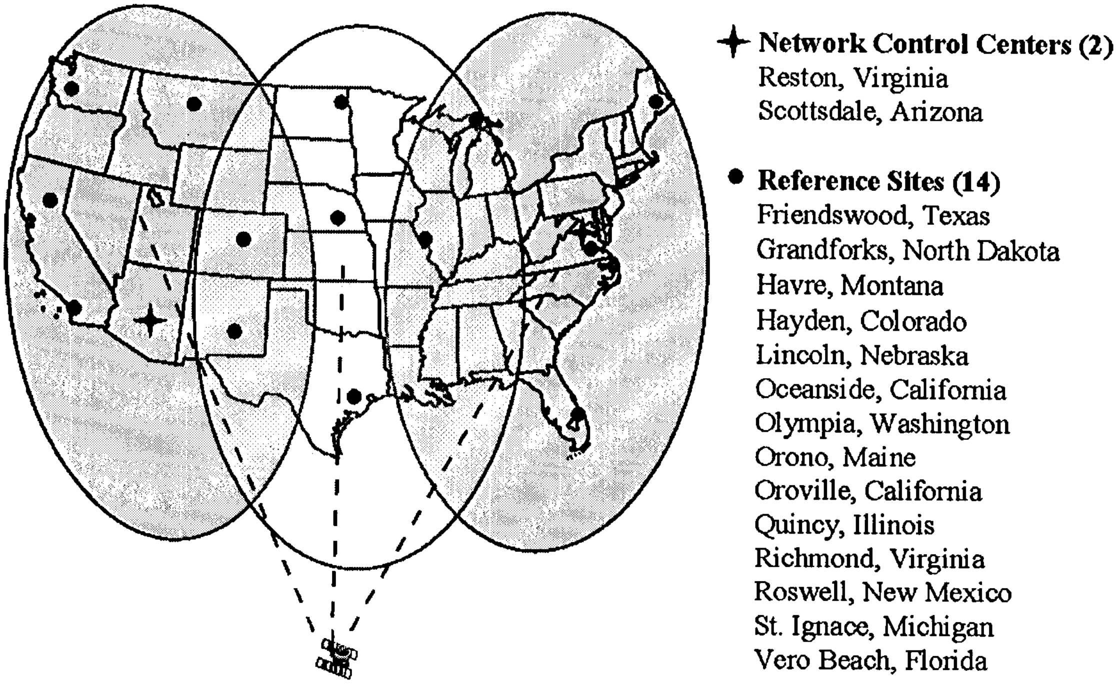

Figure 1. Satloc WADGPS reference sites and approximate spot beam pattern.

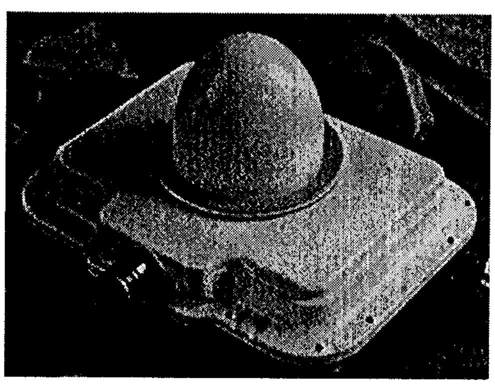

Figure 2. Satloc L-Band receiver with integral antenna.

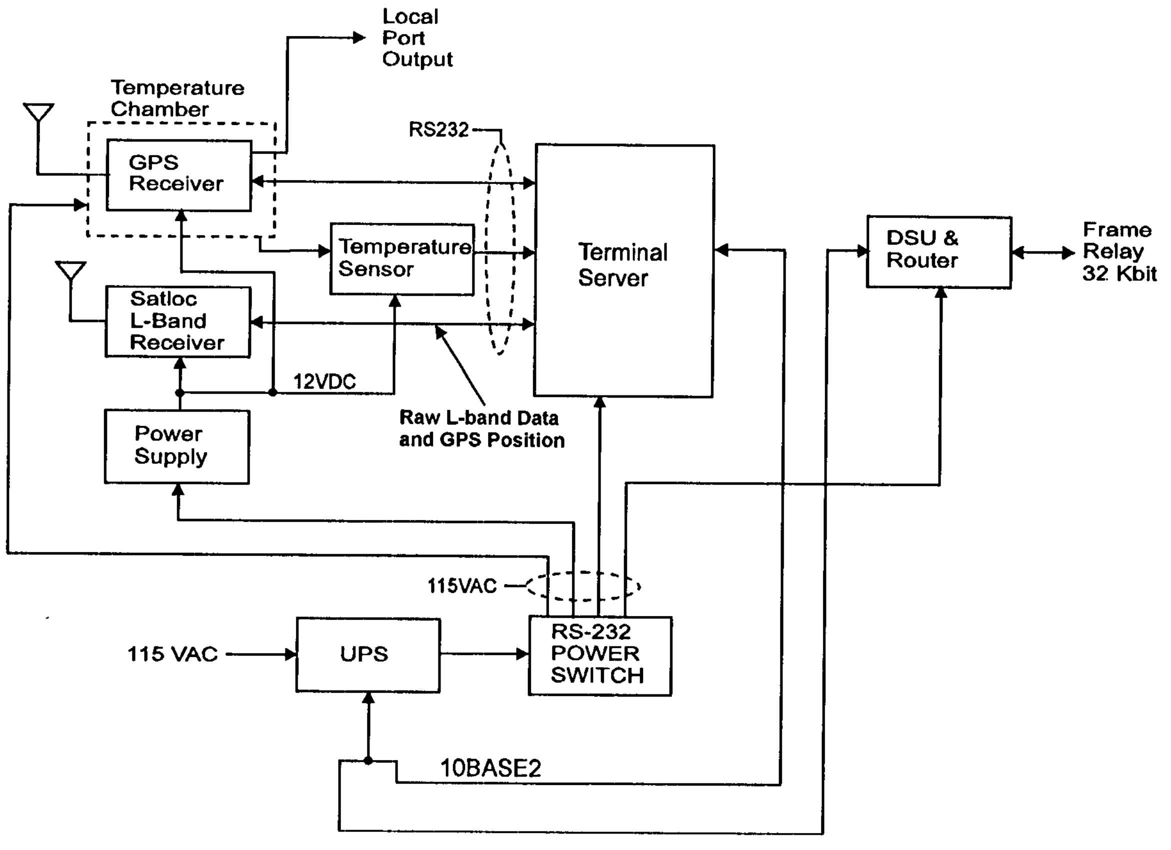

Figure 3. Reference site schematic.

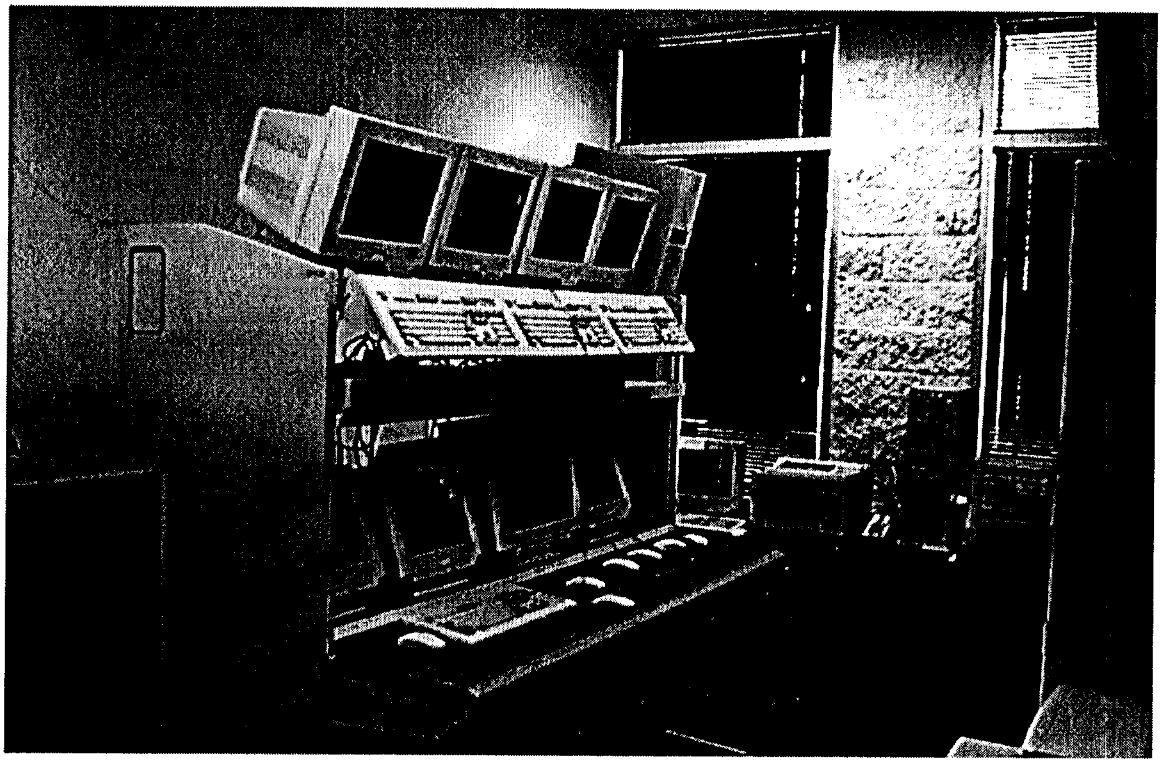

Figure 4. Satloc's Network Control Center (NCC) in Scottsdale, Arizona.

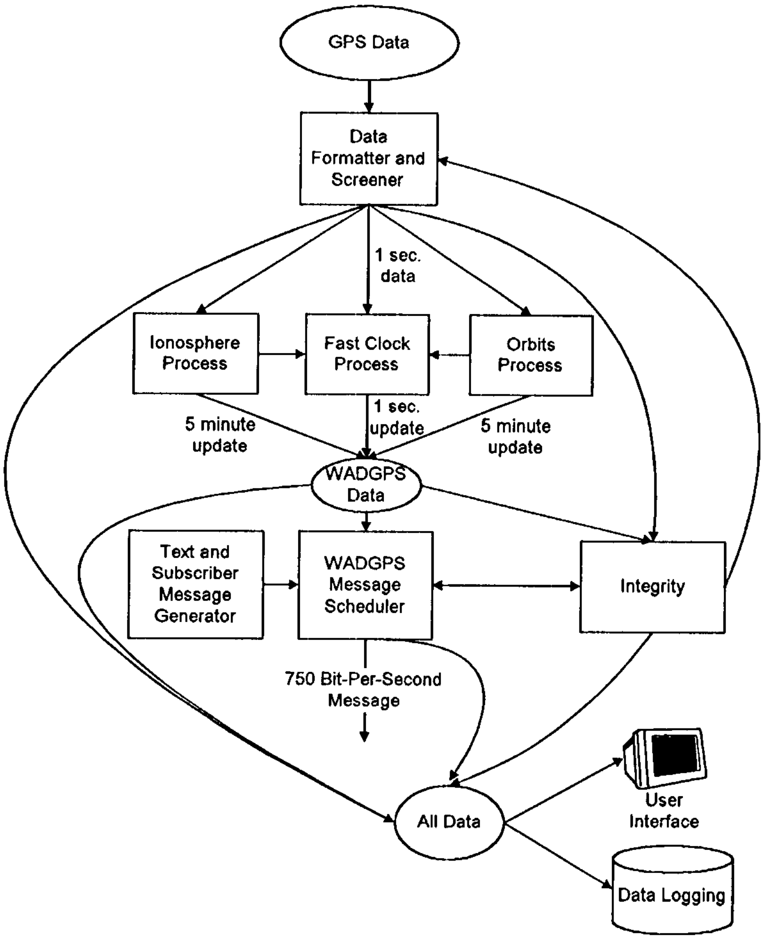

Figure 5. Simplified software flow diagram.

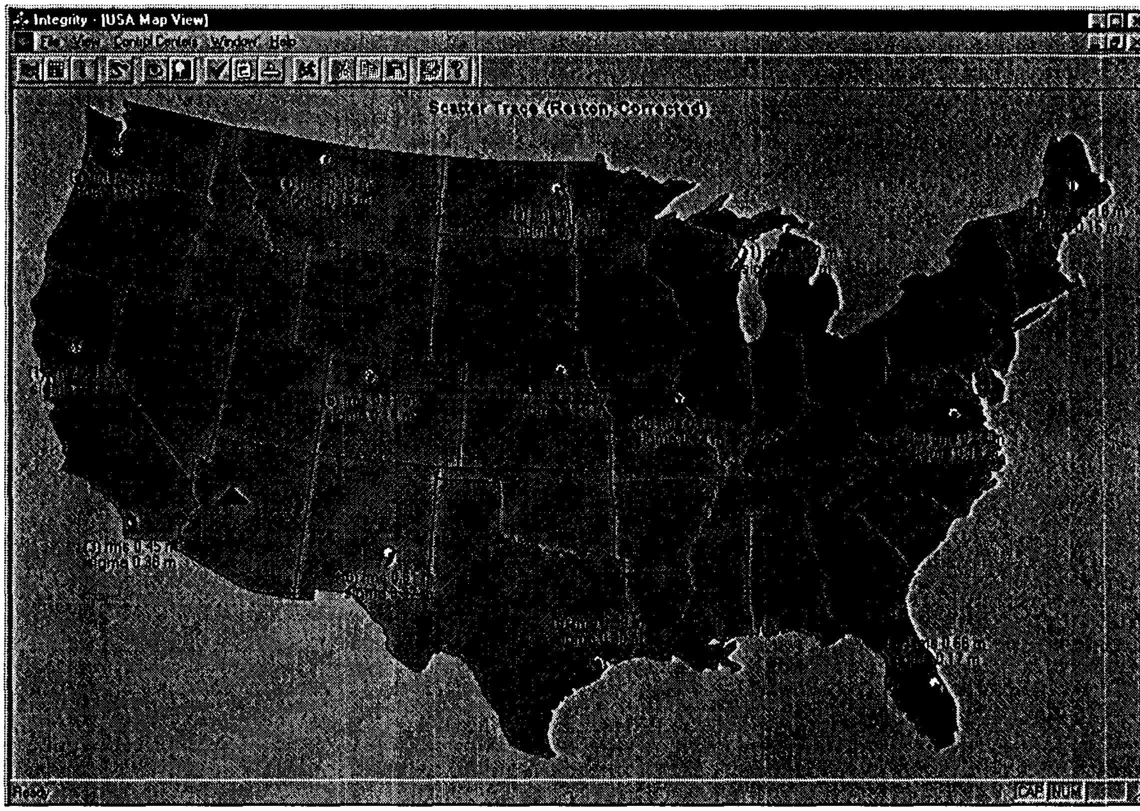

Figure 6. Software display window showing scatter diagrams of positional errors (small dark regions) over the past 15 minutes.

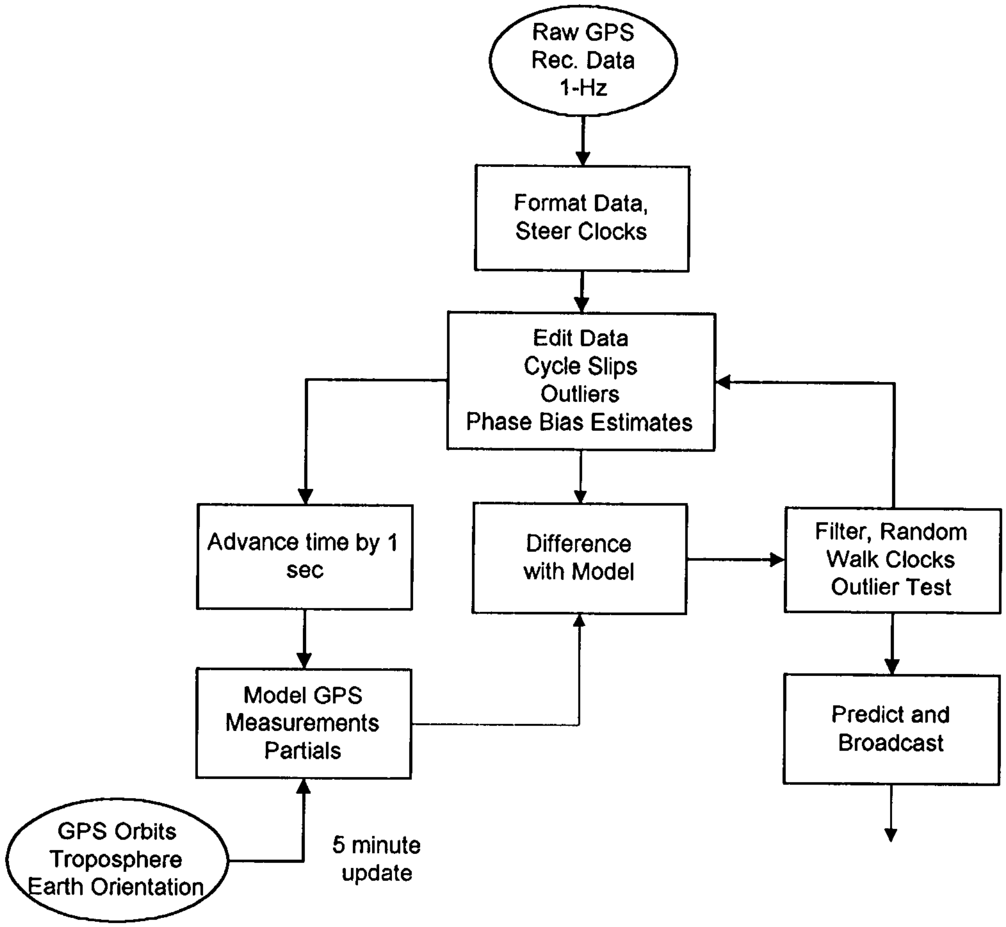

Figure 7. Fast Correction Processing Block Diagram.

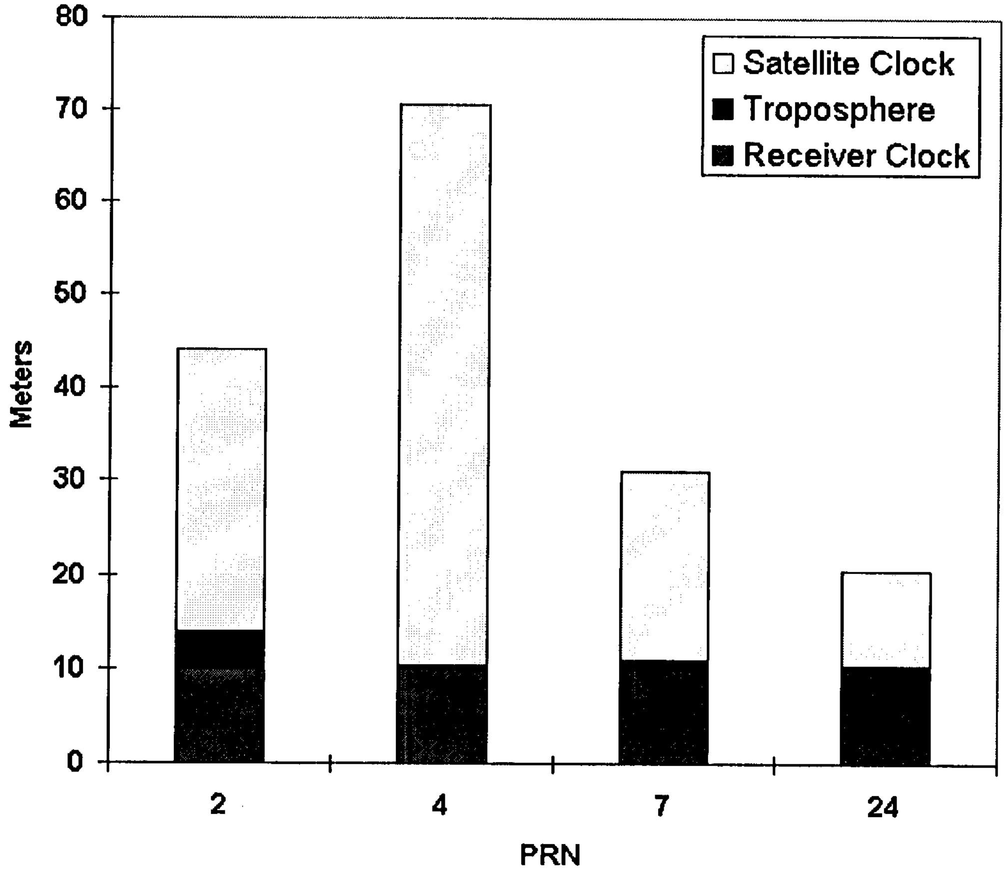

Figure 8. Example showing typical components of "SAmeas" for 4 satellites (noise components are not shown). "SAmeas" is a pseudorange error term computed by the software.

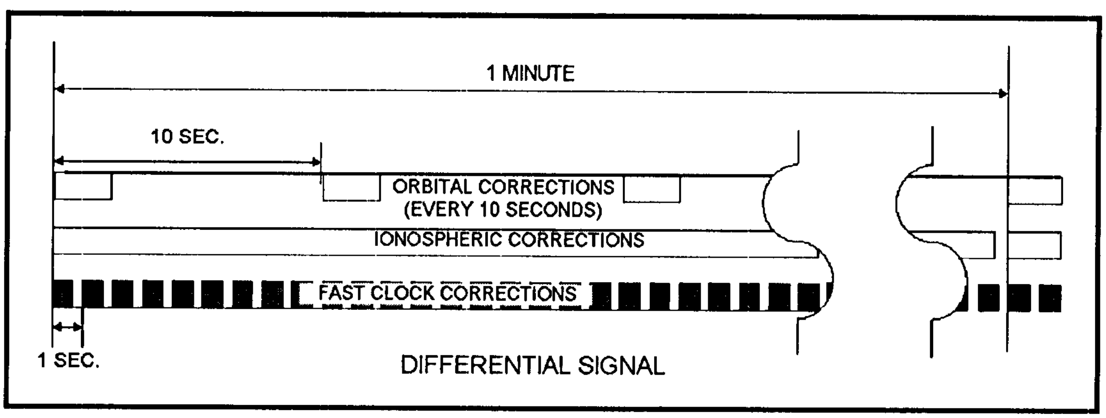

Figure 9. Approximate timing relationships for Satloc's WAGDPS correction signal.

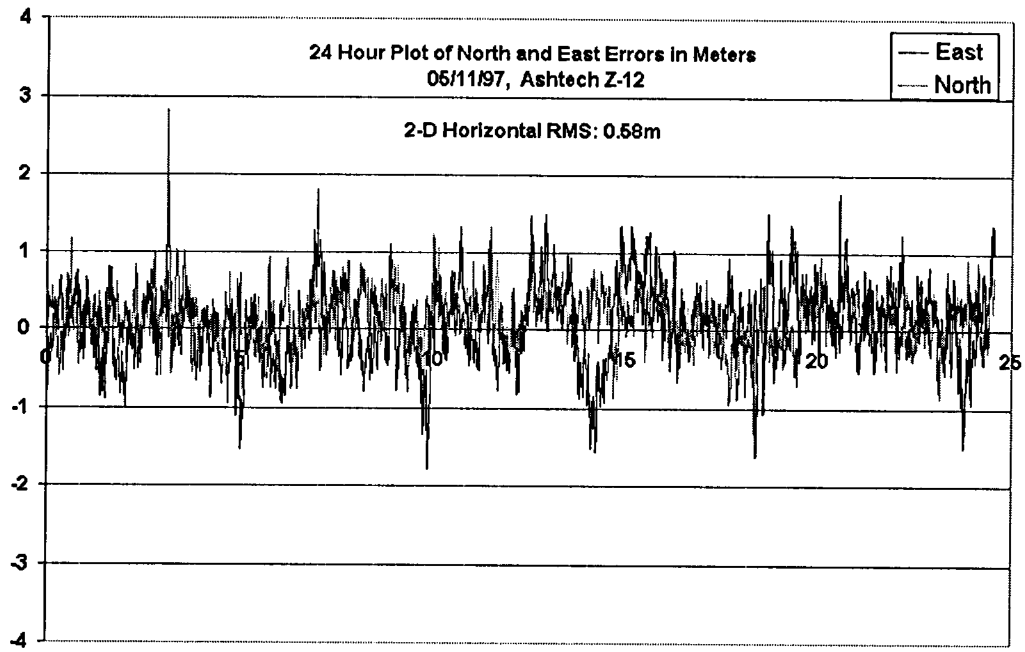

Figure 10. Stationary position result using an Ashtech Z-12 GPS receiver, corrected with Satloc's WADGPS signal.

Biographies

Mike Whitehead received his Ph.D in Electrical Engineering from the University of Florida in 1986. He developed the software which serves as the backbone for SATLOC's Wide Area Differential System. This includes clock-filter algorithms, communications, integrity, and user interfaces. Most of Mike's past work experience has involved a combination of software, signal processing and control.

Gary Penno received his BSc. in Geomatics Engineering from the University of Calgary in 1995. At Satloc Gary has focused on the development of high accuracy DGPS systems. He is responsible for differential receiver software and algorithms including the software for Satloc's WADGPS L-Band Receiver.

Walter Feller received a bachelor of Electrical Engineering in 1985 at Lakehead University in Thunder Bay, Ontario, Canada. Walter has been the lead engineer in charge of the hardware development for Satloc's L-Band differential receivers. He is the inventor /co-inventor on three patents relating to antennas and electromagnetic sensors.

Ivan Messinger received his B.S. in Forestry and Wildlife Biology at Mississippi State University. Ivan has worked with the Wyoming Cooperative Research Unit on Terrestrial Carnivore habitat usage, and the Mississippi State Department of Wildlife and Fisheries on ungulate research. Most of Ivan's experience is in GIS, data analysis, and GPS/DGPS applications. Ivan is currently the Product Applications Engineer at Satloc working on new product development and analysis.

Willy Bertiger received his Ph.D. in Mathematics from the University of California, Berkeley, in 1976. In 1985, he began work at JPL as a Member of the Technical Staff in the Earth Orbiter Systems Group. His work at JPL has been focused on the use of GPS, including high precision orbit determination, positioning, geodesy, remote sensing, and wide area differential systems.

Ronald J. Muellerschoen received a B.S. degree in physics at Rensselaer Polytechnic Institute and a M.S. degree in applied math at the University of Southern California. A member of the Earth Orbiter Systems Group at JPL, he specializes in efficient filtering and smoothing software for precise orbit determination and geodesy with GPS and development of wide area differential systems.

Byron Iijima received his Ph.D. in physics from MIT. He's currently active in ionospheric calibration for satellite ocean altimeters and WADGPS.

Greg Piesinger received his MSEE in 1968 from the University of Nebraska. Piesinger has primarily worked in the areas of communication and radar systems for such companies as Bell Telephone Labs, Motorola, and Honeywell. In 1995, he joined Satloc where he served as project
leader for the L-band network. Currently he works as a consultant through his own company Dyco, Inc. of which he is president.

Biographies

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Willy Bertiger received his Ph.D. in Mathematics from the University of California, Berkeley, in 1976. In 1985, he began work at JPL as a Member of the Technical Staff in the Earth Orbiter Systems Group. His work at JPL has been focused on the use of GPS, including high precision orbit determination, positioning, geodesy, remote sensing, and wide area differential systems.

Ronald J. Muellerschoen received a B.S. degree in physics at Rensselaer Polytechnic Institute and a M.S. degree in applied math at the University of Southern California. A member of the Earth Orbiter Systems Group at JPL, he specializes in efficient filtering and smoothing software for precise orbit determination and geodesy with GPS and development of wide area differential systems.

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